

SDC SOLENOID DESIGN NOTE #164

TITLE: Shielding Conduit for Solenoid Power Bus

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The question was raised as to the need for electrical shielding around the bus that will supply current to the detector solenoid. The bus is expected to be supplying about 8 kA at 30 VDC. Since the large inductance of the solenoid is expected to eliminate variations in the current, the voltage noise would be the only concern. However, a considerable amount of voltage noise would be eliminated by a properly designed spike trap and filter on the output of the power supply. Enclosing the bus in an aluminum or galvanized sheet metal conduit would only be necessary for electrical shielding in the event that there was a degradation in the power supply filter.

However, the bus may, for safety reasons, need some means of physical protection beyond the materials or methods used for insulating the bus. A closed metal conduit enclosing both conductors of the bus could supply this physical protection as well as provide additional electrical shielding. In this case the conduit should be grounded at the physical point where the power supply is grounded.

After the filtering, grounding, and shielding of the solenoid power supply has been ensured, the spikes and noise generated by the power supply will still be flowing in the ground. If proper grounding and shielding techniques are not used in the rest of the detector instrumentation, the noise generated by the power supply may still show up. Attached are two chapters from the text "Grounding and Shielding Techniques in Instrumentation" by Ralph Morrison (John Wiley, New York, 1977). This material helps in expressing the importance and complexity involved in proper grounding and shielding.

energy stored in a configuration of components thus rests both in the inner space of the components and in the space between interconnecting conductors. Obviously when the frequency of interest is high enough, the energy stored in the components disappears and the conductor geometry becomes a distributed component system.

If one keeps field concepts in mind, the transition from discrete circuits to high-frequency rf circuits is continuous; rf is no longer a separate phenomenon. This book attempts to show that an understanding of field concepts provides the best basis for understanding grounding and shielding problems. It also serves well to bridge the gap with rf phenomena.

3

Applying Electrostatics to Practical Processes

3.1 GENERAL

The electrostatics discussed in Chapters 1 and 2 provide the basis for much of the circuit behavior found in instrumentation. The bridge from electrostatic behavior to dynamic or ac phenomena is a short one. It is unfortunate that the concepts applied to electrostatics get pushed aside so easily once this step has been taken. Circuits are not always confined to interconnecting wires and to discrete elements, and the concepts of electrostatics explain much of this resulting phenomena.

Magnetic processes are not to be avoided. They are bypassed for the moment for convenience. This omission creates no loss at this time.

3.2 CURRENT IN CAPACITORS

The idea that a conductor or a group of conductors can hold a charge has been discussed. These charge distributions result in electric fields E and potentials V at points in space and on the conductors. Induced charges result in earthed or grounded conductors. The potential-charge relationships between elements of a system are defined by the geometry of the system. These ratios are the familiar capacitances and elastances of the system.

If the potential differences between elements are varied, the charges must adjust according to Eq. 2.4(1). The fact that the charges do vary implies a current flow. If an induced charge changes, then the current

loop is required for current flow seems to be violated. This difficulty is explained by thinking of the changing electric field between the conductors as being the equivalent of current flow. This idea does provide the missing link that closes the current loop.¹

In Figure 3.2 the change in induced charges Q_2 and Q_3 constitutes the reactive current flow. These charges reside at the zero potential of conductor ④, the earth plane.

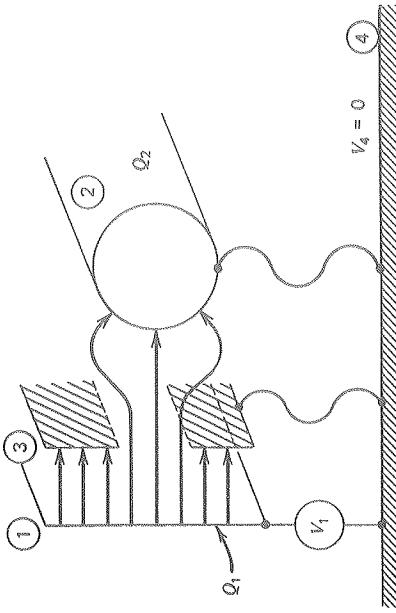


Figure 3.2 An example of self- and mutual capacitance.

flows in the earth plane. The charge in an element that is isolated or free from contact with other conductors cannot change. Current must flow in the wires or conductors forcing the change in potential.

Consider the self-capacitance C_{11} and the mutual capacitance C_{12} in Figure 3.2. If a mechanism V_1 exists for altering the charge Q_1 and if $V_2 = V_3 = 0$ (note that these conductors are connected to a zero potential), then

$$Q_1 = c_{11}V_1 \quad \text{and} \quad Q_2 = c_{12}V_1 \quad (1)$$

Differentiation of (1) yields

$$\frac{dQ_1}{dt} = c_{11} \frac{dV_1}{dt} \quad \text{and} \quad \frac{dQ_2}{dt} = c_{12} \frac{dV_1}{dt} \quad (2)$$

but the derivative of charge is current I , therefore

$$I_1 = c_{11} \frac{dV_1}{dt} \quad \text{and} \quad I_2 = c_{12} \frac{dV_1}{dt} \quad (3)$$

If V varies sinusoidally, that is, $V = V_m \sin \omega t$, then

$$I_1 = V_m \omega c_{11} \cos \omega T \quad (4)$$

The ratio of voltage to current is reactance X_c :

$$X_{c11} = \frac{1}{\omega c_{11}} \quad X_{c12} = \frac{1}{\omega c_{12}} \quad (5)$$

The flow of current I_1 or I_2 takes place in conductor ④ (the common zero potential) and in the voltage source V_1 . The idea that a complete

3.3 VOLTAGE SOURCES

Many mechanisms exist that generate differences of potential. It is not the intent in this section to discuss the physics of potential generation but it is meaningful to mention a few typical sources. They include batteries, solar cells, thermocouples, or static potentials built up by friction. There are also potentials developed from changing magnetic-flux linkages, from the power mains, or from piezoelectric effects. However these potentials are generated, whether statically or time varying, they are carried on conductors to points of reference for application. These conductors are usually wires or cables, and wherever these conductors go an electric field containing electrostatic energy must also follow. If these potentials are time varying, currents flow in all the self- and mutual capacitances of the system. Figure 3.3 shows the electrostatic field around conductors attached to a 6-V battery.

The work required to move a unit charge from A to B over any path is 6 V. The battery furnishes this work when charge is moved through the battery. Since the static charges on conductors A and B are determined by the potential difference and the capacitance, no additional accumulation or modification of static charge is possible. If charge is moved it must flow in some load connected between the two conductors to avoid changing the charge on the conductors.

¹ Maxwell's equations require the term $\partial D / \partial t$ which is called the displacement current. See Ramo Winnenry, "Fields and Waves in Modern Radio," pp. 180-183. Wiley, New York, 1959.

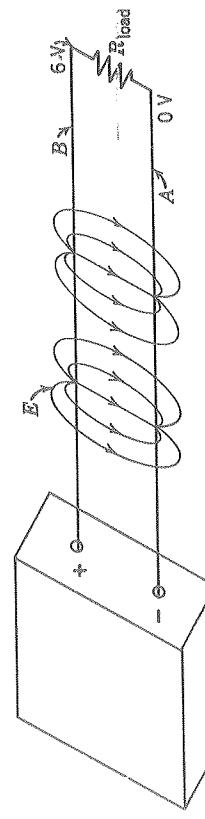


Figure 3.3a The electrostatic field about conductors and a battery.

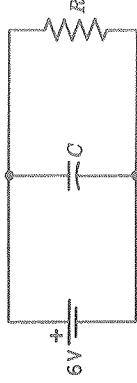


Figure 3.3b The circuit representation of Figure 3.3a.

When the structure in Figure 3.3a is examined in a circuit sense, as in Figure 3.3b, it is obvious that charge flows at a steady rate in the resistor R but remains static in the capacitor C . This circuit is very elementary but it is presented to show how closely tied electrostatic concepts are to circuit ideas.

3.4 ELECTROSTATIC SHIELDING

The word shield is commonplace in electronics. The idea is deceptively simple and yet is a source of much difficulty. The idea takes on the form of shielded wires, shield plates, shield boxes, metal screens, etc. Electrostatic shielding is just the property of Figure 2.5b. When conductor ② surrounds conductor ①, then the potential on ① cannot influence the charge on any other conductor. Stated another way, mutual-capacitance terms such as c_{13}, c_{14}, \dots , and so on, are zero. In practice these mutual-capacitance terms are not zero and they do permit unwanted effects. This problem will be treated in detail in Chapter 4. Conductor ② is called an electrostatic shield, or just a shield.

The mutual-capacitance terms between conductors within a shield to conductors outside of a shield are zero. If there are several conductors within the shield enclosure the mutual-capacitance coefficients of these conductors are not zero. The values of these capacitances will vary depending on the geometric relationships between these inner conductors and the shield conductor itself.

It is very commonplace to talk about grounding the shield. This is somewhat equivalent to the earthing of conductors required in Section 2.4. The intent there was to guarantee that all conductors were at zero potential so that the mutual-capacitance terms could be easily calculated. Grounding the shield is a more sophisticated problem and is treated fully in Section 4.4. It is correct to say that a shield can be at any potential and still provide shielding. This statement is true in the sense that relative changes in the conductor potentials within the shield have no influence on conductors outside of the shield. Also, changes in the potentials of the conductors outside of the shield have no effect on the

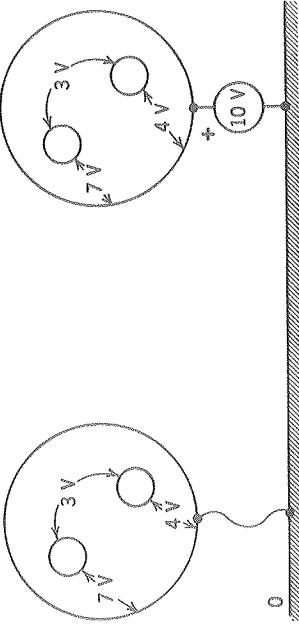


Figure 3.4 Shielding effect of a conductive enclosure.

relative potential of conductors within the shield. These statements do not require that the shield be earthed or defined in any way. The only requirement is that the conductors under discussion be fully surrounded by a conducting surface. This property is demonstrated in Figure 3.4. The potential differences for conductors within the shield in case (a) remain the same after the shield has been externally charged to 10 volts as in case (b). Note that the conductors within the shield are insulated. The internal potential differences exist only because of charges on these conductors. Unless these charges are altered, the potential differences remain the same.

3.5 THE EARTH PLANE

Every conductor has a finite resistance and the earth is no exception. The earth is used as a conductor in power systems and potential differences exist between points on the earth. For this reason one must be careful before considering the earth as a zero of potential. If one point is defined as zero potential, then the assumption that a nearby point is also at zero potential will usually be incorrect.

The electrical properties of the earth vary with the seasons of the year and with geographic location. The high-frequency or rf characteristics are not the same as power or low-frequency characteristics. Because of these unknowns the earth is usually not used as a signal-carrying conductor in instrumentation. Its influence cannot be avoided, however, as test structures, buildings, ac power, and so on, are all ohmically involved with the earth. These connections are unavoidable and result in some basic problems in instrumentation. Subsequent chapters deal with these earth ties and the best practices to minimize their effects. The earth as a conductor is discussed in Chapter 10.

Table 3.1 Table of Typical Capacitances

Description	Capacitance
½-W carbon resistor, end to end	1.5 pF
2-cm-diameter sphere, $\frac{1}{4}$ " spacing	1.11 pF
Parallel plates, $\frac{1}{4}$ " spacing/ft ²	114 pF
Two twisted No. 23 wires, HF insulation, per foot	25 pF
Center wire to shield, RG 58, per foot	20 pF
Two-wire shielded conductors, No. 1 and No. 2 under a shield conductor No. 3. Capacitance per foot	33 pF
c ₁₃	64.9 pF
c ₁₁	77 pF
c ₁₂	43 pF
Outer shield capacitance to an earth plane (RG 58 on a tray) per foot	25 pF
Mutual capacitance from	
(a) Center wire of an RG 58 cable to a metal tray, per foot	0.15 pF
(b) Center wires of a two-conductor shielded cable to a metal tray, per foot	0.5 pF
Primary-to-secondary capacitance of a 20-W transformer Case-to-circuit of an HP200CD oscillator	0.001 μF
Soldering iron element to case (20-W)	610 pF
Man standing on an insulator to earth	40 pF
Relay coil to relay framework	700 pF
Pin-to-pin capacitance on an Amphenol connector	50 pF
Bonded strain-gage element to structure	2 pF
Thermocouple to structure	140 pF
Crystal transducer to case	100 pF
Capacitance of one No. 22 insulated wire in a bundle of No. 22 wires, per foot	30 pF
2N192, element-to-case	40 pF
AB potentiometer, case-to-element	2.5 pF
	17 pF

3.6 TYPICAL CAPACITANCES

A group of representative capacitances are listed in Table 3.1. These values should be used with some caution as they are in many cases only approximate.

3.7 ROOM PICKUP

An electrostatic field at power frequencies exists in most inhabited areas. This field results from various forms of lighting, power distribu-

tion, zip cords, powered instruments, machinery, and so on. The field originates on open wiring and terminates on various grounds or conductors. In general, the field configuration is extremely complex. A person standing in a room adds to the complexity of the room's field. He assumes some ac potential other than the zero reference of a convenient piece of conduit unless he is touching that conduit. For this reason, a person is often described (improperly) as an antenna in that he picks up or couples power-frequency potentials.

A room can be thought of as a large capacitor. The lighting and conductors in the ceiling are one side of the capacitor and the floor or earth is the other side. A person in a room is literally standing in the middle of a capacitor.

The potentials in the middle of a typical room are difficult to measure. The presence of a probe or conductor for a measurement defines a new field with an equipotential along the path of the inserted conductor. With the field so modified, any measurement is invalid.

If a probe can be properly inserted to measure potential differences, the probe must not require charge or current to function as none is available in the free space. An instrument capable of measuring the field must therefore supply its own charge so that the field being measured is not modified by the process. It should be apparent that a plot of the electric field in a room would be almost impossible to make. This does not alter the fact that the field exists.

The induced reactive current flow per square foot of surface area in the earth plane of a typical room is about 100 nA at 60 Hz. This number can vary considerably and it should be used with caution. At power voltages this is an effective capacitance of about 2 pF.

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Pg. 33 - 48

4

Practical Shielding of Instruments

4.1 THE AMPLIFIER SHIELD

Consider an electronic device completely contained within a metal box. Further assume that the device is self-powered and no circuit conductors enter or leave the box. This circuit, as shown in Figure 4.1a, is completely shielded from external electrostatic influences (see section 3.4). The symbology indicates that a potential difference V_{13} between conductors ① and ③ is amplified to the value $-AV_{13}$ and this potential difference V_{23} appears between conductors ② and ③. Conductor ④ is called the zero signal reference conductor as it is common to V_{13} and V_{23} . Mutual capacitances can be calculated by 2.4(1), but generally, for a typical circuit, would involve literally hundreds of conductors. The mutual capacitances that involve the shield enclosure are of present interest. The significant capacitances for an element of gain are shown

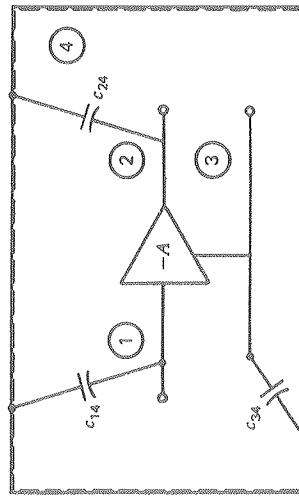


Figure 4.1a Mutual capacitances to the shield enclosure.

in Figure 4.1a. The effect of these capacitances upon the operation of the gain element becomes apparent in the equivalent circuit in Figure 4.1b. The mutual capacitances form a feedback structure around the gain element. These capacitances cannot be avoided but the obvious feedback process can be eliminated by ohmically tying the shield enclosure to conductor (3). This shorts out capacitance c_{34} leaving only capacitance c_{14} and c_{24} . This circuit is shown in Figure 4.1c. The feedback capacitances of Figure 4.1b are related to the geometry of the conductors. The placement of conductors could reduce this feedback but the preferred solution takes the form of Figure 4.1c.

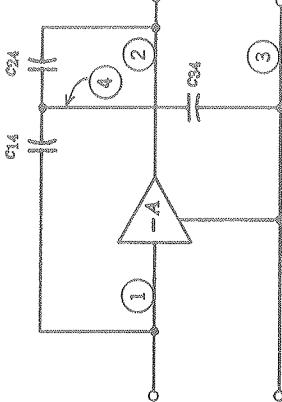


Figure 4.1b Mutual capacitances shown as circuit elements.

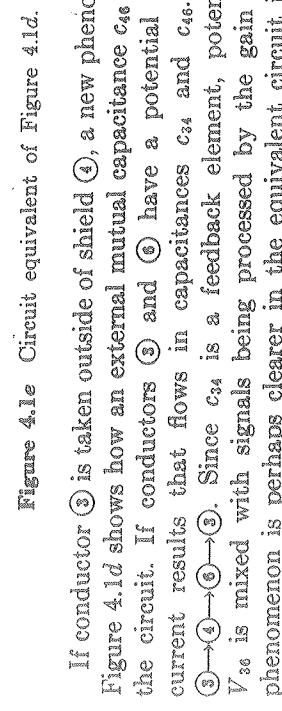


Figure 4.1c Elimination of undesirable feedback by eliminating c_{34} .

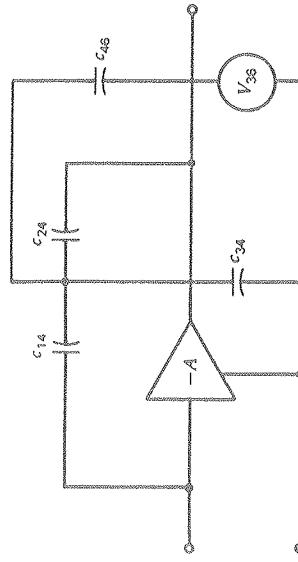


Figure 4.1d Circuit equivalent of Figure 4.1a.

If conductor (3) is taken outside of shield (4), a new phenomenon results. Figure 4.1d shows how an external mutual capacitance c_{46} now influences the circuit. If conductors (3) and (6) have a potential difference V_{36} , current results that flows in capacitances c_{34} and c_{46} . The path is (3) \rightarrow (4) \rightarrow (6) \rightarrow (3). Since c_{34} is a feedback element, potential difference V_{36} is mixed with signals being processed by the gain element. This phenomenon is perhaps clearer in the equivalent circuit in Figure 4.1e. Again this influence is eliminated when c_{34} is shorted out.

The first rule of shielding results from the foregoing discussion.

Rule 1. An electrostatic shield enclosure, to be effective, should be connected to the zero-signal reference potential of any circuitry contained within the shield.

Conductor (3) exits the shield (4) in Figure 4.1d. This would appear to be acceptable provided Rule 1 above is followed. This conductor is then an extension of the shield and does not violate the shield-enclosure idea. Problems do result, however, and these are treated in the following sections.

4.2 SIGNAL ENTRANCES TO A SHIELD ENCLOSURE

The gain element in Figure 4.1a is impractical without input and output connections. Conductors that carry the signal to and from any amplifier are called signal conductors. For example, conductors (1) and (3) are signal conductors in Figure 4.1a. Signal conductors are usually enclosed in a braided metallic sheath or shield, and this cable is called shielded wire. If two conductors are within the shield it is called two-conductor shielded wire. This shielded wire is used to transport the signal from its source to the amplifier and can be thought of as an extension of the electrostatic enclosure of Figure 4.1a.

A shield enclosure is effective when Rule 1 is applied. This rule places no restriction on the shield potential relative to the external environment. This is the key to connecting signal conductors to a gain element. Since

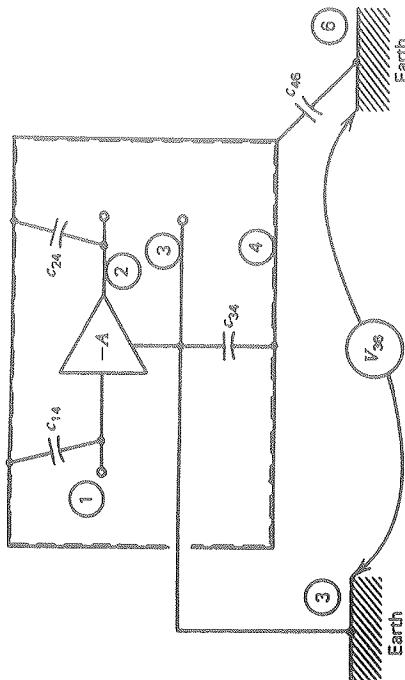


Figure 4.1d Conductor (3) tied externally.

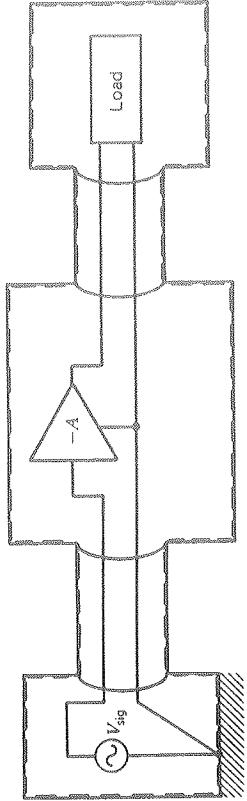


Figure 4.2 An extended shield enclosure including signal lines.

the shield must be at zero-signal reference potential, and since the signal is often derived from some reference point in the external environment, the shield is automatically defined at this external reference potential. There is no other choice.

Figure 4.2 shows a gain element and its shield enclosure. The input and output connections are two-wire shielded conductors. The input signal zero is ohmically connected to an earth point. When the shield is tied to this same earth potential Rule 1 is applied and the system is correct. This statement is very important:

Rule 1 requires that the shield must be tied to zero-signal reference potential. If the signal is earthed or grounded, the shield becomes earthed or grounded. Earthing or grounding the shield makes no sense if the signal is not earthed or grounded.

4.3 SHIELD CURRENTS

The electrostatic enclosures shown in Figure 4.2 often parallel several external conductors. For example, long runs of shielded wires are contained in raceways, in conduit, in floor wells, in parallel with other wires, in racks, or along floors. These neighboring conductors (grounds) are usually at differing potentials. In particular, these potentials are not the zero-signal reference potential of the shield enclosure.

These neighboring potentials cause currents to flow in the mutual capacitances between conductors. In Figure 4.3, current flows in loops such as ①→②→③→① or ①→③→④→⑤→①. This current flows in shield segments only and not in signal conductors. If this were to happen, unwanted pickup would result.

4.4 SHIELD.DRAIN DIRECTION

Rule 1 requires that the shield be connected to zero-signal reference potential. No statement is included as to where this connection should

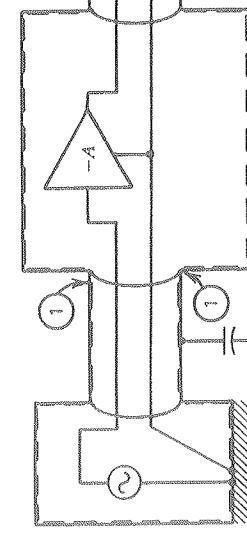


Figure 4.3 Mutual capacitances between an electrostatic enclosure and other earths and grounds.

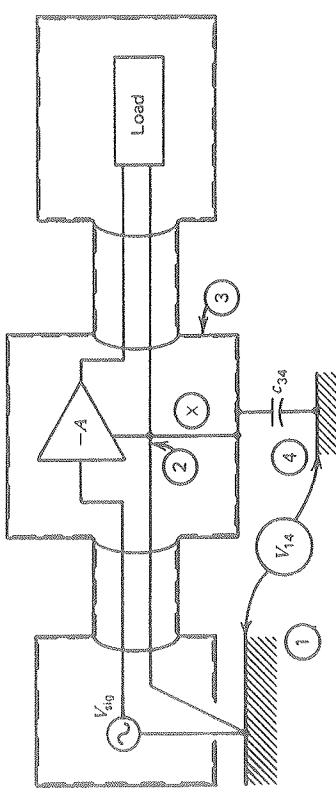


Figure 4.4 An incorrect tie between shield and the zero-signal reference potential. The connection is correctly made in Figure 4.2. An incorrect connection ⑧ is made in Figure 4.4 to illustrate the difficulty. The potential difference V_{14} causes current to flow in capacitance c_{34} in loop ①→②→③→④→①. If current flows in signal conductor ②, unwanted pickup results. To avoid this process, a second rule can be formulated.
Rule 2. The shield conductor should be connected to the zero-signal reference potential at the signal-earth connection.

This procedure ensures that parasitic currents will flow in the shield only and not flow in the signal conductors. The shield can be thought of as a drain path to carry unwanted current back to an earth point. Stated again:

Rule 2 requires that shields be connected so that shield currents drain to signal-earth connections.

The pickup that results from unwanted current flow in a signal conductor depends on cable length, frequency, and conductor size.¹ A possible problem occurs when the pickup magnitude approaches that of the signal being amplified in the frequency band of interest. Some systems have filters that electrically screen out these undesirable signals. This discussion is perfectly general and is intended to show the mechanics of pickup, not to argue whether the rules should or should not be followed.

4.5 SHIELD CONNECTIONS—SEGMENTS

By Rule 1, the electrostatic enclosure should be at zero-signal reference potential. If the shield is split in sections *Rule 2* places a constraint on the treatment of these segments. The rule requires that the shields be tied in tandem as one conductor and then connected to zero-signal reference potential at the signal-earth point. If the shield segments are individually treated the difficulties exhibited in Figure 4.4 can be expected.

Rule 2 is sometimes intentionally violated within an instrument amplifier. This problem is treated in Section 4.13. Shield connections that permit current to flow in an output or high-signal-level conductor are often ignored. The pickup here, as a percentage effect, is usually very low. Shield-drain processes in input conductors should be closely watched as the pickup here is subject to amplification. It is usually not too difficult to follow *Rule 2* everywhere to avoid this and other difficulties that can result.

Rule 2 can be followed only when two-conductor shielded wire is used, as in Figure 4.2. Single-shielded wire (coax) obviously requires that the shield and zero-signal reference conductor be one and the same. Since unwanted current can only flow in the shield, pickup cannot be easily controlled with this type of cable. Fewer problems result when output cables are coaxial but new problems such as cross talk can arise. These effects are discussed in subsequent chapters. Also see the notes on shielding charge amplifiers in sections 6.3 and 6.4.

¹ Reactive currents of up to 1 mA often flow in circuits such as Figure 4.1d. If conductor ③ is 10 ft of No. 25 wire, its resistance is 0.32 Ω and the pickup is 0.32 mV rms. At the output of an amplifier with gain of 1000 this is 0.9 V peak-to-peak, a sizable signal indeed.

Even when the pickup is outside the band of interest, filtering may be ineffective. This results when nonlinear effects such as rectification occur and when the filtering is placed after the point of nonlinearity. Since the nature of the pickup cannot always be predicted, it appears worthwhile to take heed and follow good instrumentation practice.

4.6 POWER ENTRANCES

The instruments described in previous sections require operating power. Utility power is preferred over alternate sources such as batteries or solar cells. These alternate sources contain no 60-Hz influences but they are generally impractical. The use of utility power poses problems but the resulting ac effects can be reduced to acceptable levels.

If transformer action is employed, power can enter a shield enclosure without violating *Rule 1*. In practical power transformers, the materials used for shielding are usually copper or aluminum. These materials are nonmagnetic and they do not hinder a magnetic field. The magnetic field effectively crosses the shield boundary and couples energy from the primary to the secondary of the transformer.

4.7 POWER-TRANSFORMER CONVENTIONS

It is the custom to draw a power transformer with the core shown as parallel lines between the primary and secondary coils. Since all of the transformers used in the following sections use magnetic core material, and since these core representations add nothing to the understanding, these lines will be deleted from all drawings. Effective transformer action requires that the primary and secondary coils be properly coupled magnetically. One practice that is often used places the primary coil physically over or under the secondary coil. The nonmagnetic shield used to separate the primary from the secondary coil must take on a complex shape. A simple transformer representation illustrates none of this complexity.

In practice, a transformer shield is a wrap of copper or aluminum over a coil or over several coils. It constitutes a single open turn as it usually threads the core along with the coil. As a turn it can not close on itself as this would constitute a shorted turn. A transformer with a shorted turn is considered defective.

Shields can be of differing quality. They can be simple and only fill the space between coils or they can be extended to cover the sides of the coils as well as the leads exiting the coils. They can be made electrically "watertight" or full of "leaks." In the following discussions the shields are assumed perfect to illustrate their use and effectiveness. See Section 8.4 for further treatment of shielded transformers.

4.8 POWER TRANSFORMER WITH A SINGLE SHIELD

Figure 4.8 shows a typical power-transformer entrance into a shield enclosure. The transformer has one shield ④. This shield is one segment

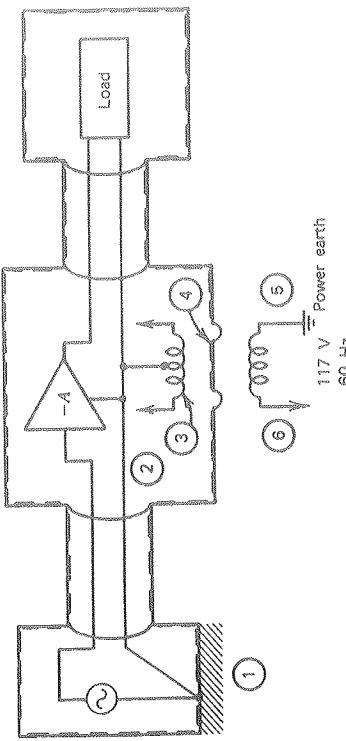


Figure 4.8 A power-transformer entrance into a shield enclosure.

of the total shield and is shown connected by Rule 2 to the remaining shield enclosure. The transformer shield is usually close to both the primary and secondary coils of the transformer. These coils have power-frequency voltages on their turns. Each turn has a capacitance to the shield and this potential difference causes current to flow in the coil-to-shield capacitance. The lumped effect of the coil-shield relationship is that of a single capacitance in series with a fraction of the winding voltage. This effect takes place on both sides of the shield and causes currents to flow in two separate paths.

4.9 COIL-TO-SHIELD CAPACITANCE

Consider a coil and shield arrangement as shown in Figure 4.9a. This coil is a single layer of conductors, each loop having a capacitance c_m to the shield. If the shield and one end of the coil are at zero potential, the current flowing in each capacitance will depend on the voltage level at each turn. Assume an n -turn coil with a potential V across the coil. The potential on the m th turn is mV/n . The current in the m th capacitance is $Vm/n \cdot 1/X_c$. The total current in all n conductors where n is large is

$$I = \sum_{m=1}^n \frac{Vm}{n} \frac{1}{X_c} = \frac{V_n}{2X_c} \quad (1)$$

The capacitance of the conductors to the shield is the parallel combination of all turns capacitances or nc_m . The current of (1) flows as if this capacitance is connected to the midpoint on the coil as shown in Figure 4.9b.

Transformer coils are usually layer-wound. The last layer of turns will be next to any shield placed over the coil. If the center tap of the coil is pulled out from an inner layer, then the shield will in general not be physically near this point. The turns in an outer layer screen the turns from all internal layers (low mutual capacitance). This means that the only turns involved in coil-to-shield reactive current flow are in the outer layer. Since the full coil has many layers, the potential difference across this last layer is usually only a fraction of the total coil voltage. For example, if 10 layers are involved in a 120-V coil, then 12 V appears across each layer. The potential difference between the midpoint and the ends of the outer layer is 6 V. If the start of the coil is at 0 V, the outer layer midpoint is at 114 V. If the start of the coil is at 120 V then the outer layer midpoint is at 6 V.

Current flow to the shield from this outer layer is described by Eq. 4.9(1). The capacitance is essentially that of the last layer of coil to the shield or nc_m . The potential differences V_n must be measured between the midpoint of the outer layer and the shield. If the shield is at zero potential and the coil end adjacent to the shield is connected to 120 V, then the potential difference forcing shield current is 114 V.

Utility power is usually furnished with one conductor at or near earth potential. The coil-shield arrangement shown in Figures 4.9a and 4.9b is thus typical of the transformer primary-to-shield conditions encountered in instrumentation.

The center-tapped secondary coil in Figure 4.8 is also typical. The preceding arguments show that the shield is rarely balanced with respect to this center tap. On the primary side the potential V_n depends on the sense of the power connection. This is why instruments with unshielded or one-shielded transformers often operate best with a preferred power-cord orientation. This discussion should make it obvious to the reader

Practical Shielding of Instruments
that transformer diagrams are quite misleading; the diagrams would imply symmetry whereas in reality there is unbalance.

4.10 THE SINGLE TRANSFORMER SHIELD AND ITS CONNECTIONS

The coils in the transformer of Figure 4.8 act as simple voltage sources in series with coil-to-shield capacitances. These potentials circulate currents in the shield structure. Figure 4.10a shows these sources and the effective series capacitances.

Assume that there is an ohmic path between the earth (1) and the earth (5) and also that these conductors are at the same potential. (If they are not at the same potential, the difference can be absorbed by adding it to the potential at (6).)

The current loop in the primary is (1)→(7)→(6)→(5)→(1). This current path is outside of the shield enclosure. The current loop for the secondary, however, is (1)→(2)→(3)→(4)→(1) and this current flows in the signal-input conductor (2) and must be considered. If c_{s1} has a $1\text{ M}\Omega$ reactance at 60 Hz, and the transformer potential difference from (2) to (3) is 5 V, then $5\ \mu\text{A}$ will flow. If the conductor (2) has 2Ω of resistance, $10\ \mu\text{V}$ of pickup will result. In many instrumentation processes this is excessive.

The transformer shield can be alternately connected to the zero-signal reference potential at the gain element. This confines the secondary circulating currents but extends the primary-coil current flow. Figure 4.10b demonstrates the new problem. The secondary current flow in capacitance c_{34} follows the loop (4)→(2)→(3)→(4). This loop does not involve the resistance in conductor (2). The primary current flow in capacitance c_{46} follows the loop (6)→(4)→(2)→(1)→(5)→(6) and this current does flow in the length of conductor (2). The calculation for the circuit in Figure 4.10a showed a $10\ \mu\text{V}$ pickup. In Figure 4.10b the same circuit values result in $200\ \mu\text{V}$ pickup. (Note: the capacitance c_{46} has $100\ \text{pF}$ as a

source potential, nearly the entire primary voltage.) This pickup is amplified by the gain element.

The shield connection shown in Figure 4.10b is the most commonly used. The difficulties it creates for the application shown in Figure 4.10b are obvious. If the external earth-signal connection is made at the output or signal-termination point, the difficulty is not as severe. Currents still flow in conductor (2), but in the output side where the pickup is not amplified by the gain element.

4.11 THE DOUBLE ELECTROSTATIC SHIELD

The current that flows in the zero-signal reference conductor in a single-shielded transformer cannot be eliminated. No placement of the transformer shield avoids the problem. In some applications the pickup effects can be minimal and a single shield is adequate.

To contain the currents caused by the transformer voltages, a second shield must be added. This shield is placed directly over the first shield but insulated from it. The shield nearest the primary coil is called the primary shield and similarly the shield nearest the secondary is called the secondary shield.

The proper connections for these two shields are shown in Figure 4.11. The secondary shield is segmented and connected to zero-signal reference potential at the gain element. The primary shield is often connected to the rack or frame of the supporting console. The primary-shield currents flow in the path (5)→(6)→(7)→(8)→(6) through capacitance c_{56} . The secondary-shield currents flow in the path (2)→(3)→(4)→(2) through capacitance c_{34} . In both of these loops, the current does not flow along the zero-signal reference conductor (2).

A potential difference usually exists between conductors (7) and (8) in

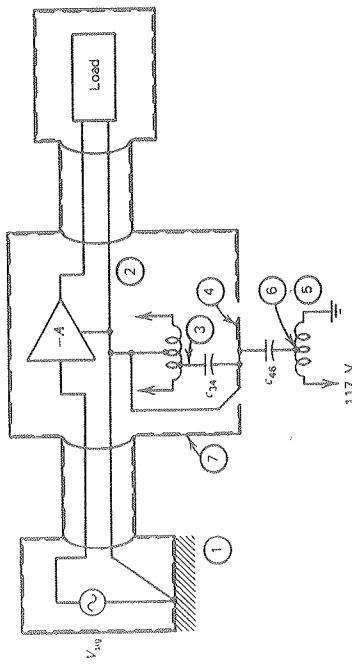


Figure 4.10a Transformer and segmented shield.

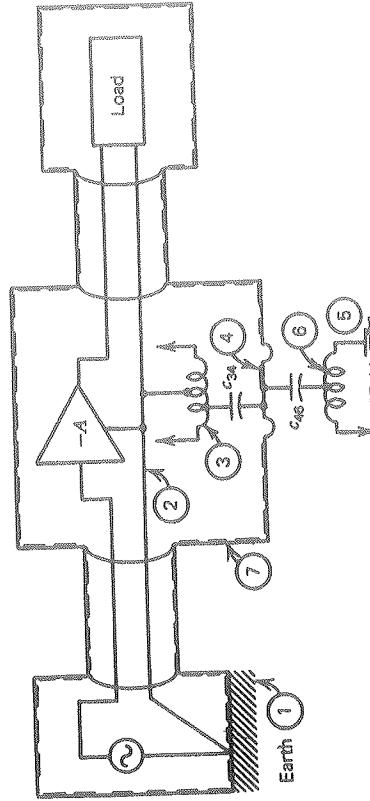


Figure 4.10b The primary and secondary capacitances.

The primary shield (conductor 8) in Figure 4.11 lies between the primary coil and the secondary shield, and serves its function by intercepting the electric flux from the primary coil. An unshielded power cord followed by a shielded segment of conduit usually follows this along the power link. The primary shielding is thus segmented, partially complete, and connected to various and unknown potentials referred to indiscriminately as ground. After the shield serves its purpose in the transformer, the full enclosure of the power distribution is not maintained. Fortunately it is not important as this procedure would be difficult indeed. For this reason the primary coil shield is not shown as a full enclosure in all diagrams.

The connection point for the primary shield in Figure 4.11 should be considered. The potential difference between earth connections ① and ⑧ will cause current to flow in capacitance C_{45} . This capacitance in a 10-W transformer may be $0.001\mu F$. The loop path is ① → ② → ④ → ⑤ → ⑧ → ① and this includes the zero-signal reference conductor. If a 10-V potential difference exists, a $3-\mu A$ current flows. In a $2-\Omega$ line this is $6\mu V$ of pickup. The proper potential for the primary shield is thus zero-signal reference potential. A connection directly to the gain-element zero-reference conductor negates the secondary shield. Therefore, the primary-

connection must be made via another path to be effective. See section 4.15 for further discussion.

The transformer shields as shown in Figure 4.11 need only be moderately good to be effective. A hundredfold reduction in effects results if the conductors within the shield enclosure have mutual capacitances to the total external environment of 5 pF or less. The leakage or mutual capacitance from the primary coil to the secondary shield is C_{46} . The leakage or mutual capacitance from the secondary to the primary shield is C_{35} . These capacitances are not drawn out as circuit elements in Figure 4.11, but they are real and do exist.

The doubly shielded transformer provides some immunity from unwanted pickup caused by reactive current flow. It should be apparent that it is not the complete solution as the effects just described may be difficult to overcome. The differential amplifiers discussed in Chapter 5 are best suited for solving this and many other problems encountered in instrumentation.

4.12 SINGLE-ENDED AMPLIFIERS

The gain element in Figure 4.11 is called a single-ended amplifier. The distinguishing feature is the through connection of the zero-signal reference conductor. This through connection can be effective as a signal-carrying element as long as unwanted current does not flow along its length. The effects of the power transformer were discussed in Sections 4.10 and 4.11. The external connection to earth were discussed in Section 4.1. If two such external connections were made large currents could flow in this conductor. If this current flows in an input segment, the pickup is amplified. Current flow in an output segment may not be as damaging, but this is a relative matter. Therefore only one point along the zero-signal reference conductor should be earthed.

A philosophy accepted in some quarters is to short out offending potential differences so that two external connections can be made to the same zero-reference conductor. Even if the potential difference can be reduced to 0.01 V, the reference conductor must straddle this 0.01-V difference. Therefore some fraction of this 0.01 V will appear as an input signal. This solution is not suggested as practical or useful but is often used as a last resort when other possibilities are exhausted.

Two external ground connections to a zero-reference conductor cause a ground loop. Current will flow in any such loop and the nature of the current will depend on many unknowns. In other words, the current level may be low enough today, but tomorrow may be another story.

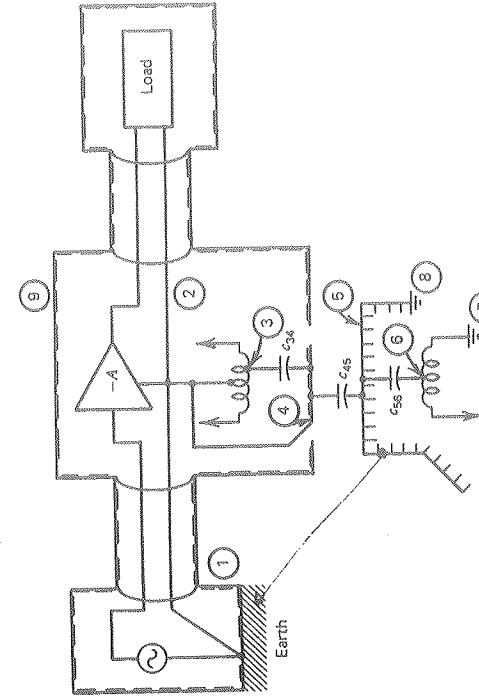


Figure 4.11 A double-shielded transformer.

4.13 SEGMENTING THE AMPLIFIER SHIELD

All efforts in shielding are directed towards reducing unwanted pickup. The procedures outlined in Section 4.11 have a practical flaw. The shield structure ⑨ in Figure 4.11 is usually in close proximity to sensitive gain elements within the amplifier. This shield is connected to one point only and this is at the signal-earth connection by Rules 1 and 2. The distance to this connection can vary from a few feet to thousands of feet. At large distances the inductive effects and transmission-line effects will allow potential differences to be developed along the shield length. See Section 4.3. If a shield has potential differences along its length, it can be at zero-signal reference potential at one point only. These shield signals can thus couple into sensitive circuitry contained within the shield.

Amplifiers are usually manufactured with the local shield segmented and connected to the zero-signal reference potential at the amplifier. This avoids the direct contaminating effects indicated above. If this were not done amplifiers would rarely meet their noise specifications. There is no loss caused by this practice as the signal brought to the amplifier by the input shield is not significantly influenced by the amplifier-shield segment. The zero-signal reference potential the amplifier sees at its input terminals cannot be improved upon. The shield may be affected by its external environment but only a fraction of this contamination couples into the signal. It therefore makes good sense to shield the amplifier with the best available measure of the zero-signal reference potential. This practice is shown in Figure 4.13.

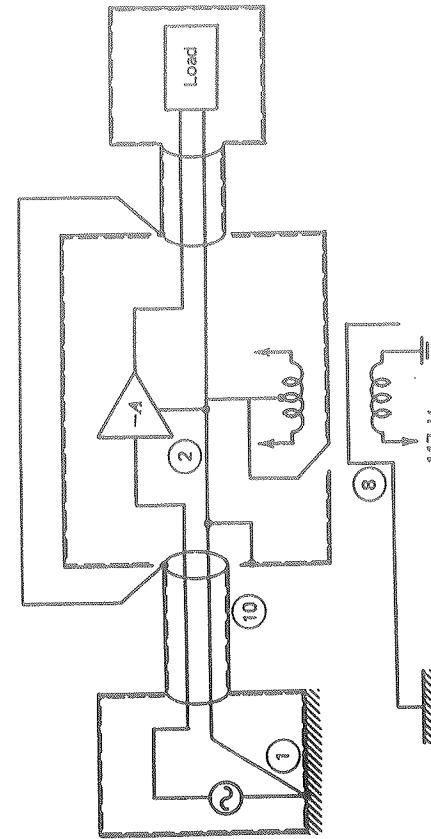


Figure 4.13 A practical double-shield system.

4.14 A SHIELD-ENCLOSURE RULE

The discussion in the preceding section on double shielding in power transformers lends insight into an important generalization. The first shield was used to surround all of the signal processes and this included signal conductors, the gain element, and the secondary of the power transformer. The second shield was used to enclose the power source insofar as it was practical and meaningful.

A third shielding rule would not be apparent from the above discussion alone. It is stated here and will be required to extend the application of the electrostatic shield in the next chapters. As the rule is applied its value will become more apparent.

Rule 3 *The number of separate shields required in a system is equal to the number of independent signals being processed plus one for each power entrance.*

The three shielding rules described in this chapter provide a basis for design. It may not always be necessary to apply them in their strictest sense; however, it is important to understand why they have been formulated. If a rule is not followed it is good design practice to understand the side effects and to calculate their magnitude if possible.

4.15 PRIMARY-SHIELD TIES

The primary shield ⑧ in Figure 4.11 should be connected to a point of zero-signal reference potential (see section 4.11). This can be accommodated by a separate conductor connecting ⑧ to ⑩. It is practical in some cases to use the shield conductor ⑩ for this connection. If a low-level signal is being processed over this long line, pickup may result because the shield current establishes a potential gradient along the shield's length. If several signals are being amplified and they originate in the same zero-signal reference environment, one conductor can be brought back for connection to the several primary shields involved. A separate wire for each instrument is not required. If a shield is used for this connection it should preferably be the shield of a high-level signal. If this is not available, the separate conductor is preferred.

A subtle advantage is gained by returning the primary shield to earth via the input shield. This approach reduces the loop area ①→②→⑧→⑩, which includes the input signal conductor ②. This loop area subjects the input to possible unwanted magnetic pickup and the proper shield return reduces this possibility.

4.16 A NOTE ON LOCATING CURRENT LOOPS

Every circuit or system has a large number of possible current loops. Some of these loops permit unwanted signal pickup. The author is frequently asked, why did you pick that loop—what is the matter with this one? Often the loop suggested is an impossible one because current would have to return to zero potential and still traverse a further impedance to make the full circle. Admittedly the circuits are not conveniently drawn out, but the circuits are simple once they have been located. The author has found it convenient to use the following rules to locate current loops involving transformer coils:

1. Start with each zero-signal reference conductor.
2. For each transformer coil referenced to this potential, locate the possible mutual capacitances (leakage capacitances) that will permit current flow.
3. From the terminating end of this mutual capacitance locate all return paths to the zero-signal reference conductor.
4. Once a current path returns to zero-signal reference it cannot proceed further.
5. Consider all ground or earth points as tied together.

The following statements will help in locating current loops involving ground potential differences:

1. Start with each zero-signal reference shield.
2. Consider the mutual capacitance to any adjacent shield.
3. If this shield is at a potential other than zero-signal reference, then current can flow in the mutual capacitance.
4. From the terminating end of this mutual capacitance locate all possible return paths to the reference shield.
5. Once a current path returns to the reference shield it cannot proceed further.
6. Consider all ground or earth points as tied together.

The Differential Amplifier

5.1 GENERAL

The words *differential amplifier* have a very general meaning. There are many instrumentation problems requiring the use of differential amplifiers but not all instruments with this generic title will prove to be useful.

Many oscilloscopes provide a differential type of input circuit. Here, a common terminal plus two input terminals, often marked *A* and *B*, provide a signal entrance. The oscilloscope pattern demonstrates the subtraction of signals applied to terminals *A* and *B*; that is, the pattern is proportional to signals $A - B$. If $A = B$ the pattern remains unaffected. The value of signal difference, $A - B$, is termed the differential signal. The average value of signal $(A + B)/2$, which is applied to both inputs, is ignored when the oscilloscope is properly balanced.

An example of this operation may be useful. Figure 5.1 shows several

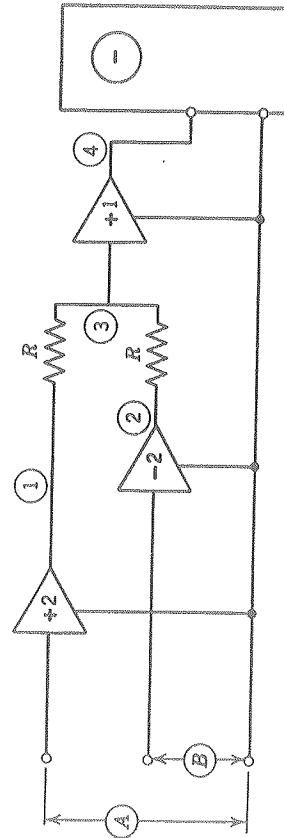


Figure 5.1 A simple differential amplifier.